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14. ABSTRACT

This research program is to develop a fundamental understanding of the damage propagation through layered transparent armors under impact loading conditions. The effects of surface quality and interfacial bonding strength on the damage propagation or arrest will also be examined. During the funded period of the program, a gas gun has been developed and used to impact layered glass targets. Notched glass specimens having adhesive interfaces are impacted with plastic projectiles. It is found that, an impact-induced crack arrests at an interface

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Report Title

Effects of Surface Treatment and Interfacial Strength on the Damage Propagation in Layered Transparent Armor Under Impact

ABSTRACT

This research program is to develop a fundamental understanding of the damage propagation through layered transparent armors under impact loading conditions. The effects of surface quality and interfacial bonding strength on the damage propagation or arrest will also be examined. During the funded period of the program, a gas gun has been developed and used to impact layered glass targets. Notched glass specimens having adhesive interfaces are impacted with plastic projectiles. It is found that, an impact-induced crack arrests at an interface perpendocular to the crack path if the interface is not bonded. When the interface is bonded tightly, the crack passes through the interface in its propagation without being affected by the interface. When the bonded interface has a finite thickness, the crack slows down at the interface and then branches to many cracks that form a fan shape. Besides the crack experiments, the effects of surface quality on bending strength of glass are also investigated.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Nie, X., Chen, W., Wereszczak, A. A., Templeton, D. W., 2009, "Effects of Loading Rates and Surface Conditions on Flexural Strength of Borosilicate Glass," Journal of the American Ceramic Society, Vol. 92 (6), pp. 1287-1295.

Sun, X., Liu, W., Chen, W., and Templeton, D. W., 2009, "Dynamic Failure of Borosilicate glass under Compression/Shear Loading: Finite Element Modeling," International Journal of Impact Engineering, Vol. 36, pp. 226-234.

Nie, X., Chen, W., and Templeton, D. W., 2010, "Dynamic Ring-On-Ring for Rates and Surface Conditions on Equi-axial Flexural Strength of Brittle Materials," International Journal of Applied Ceramic Technology, 7:616-624.

Number of Papers published in peer-reviewed journals: 3.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Hwun Park and Weinong Chen, 2009, "Experiments on Dynamic Crack Propagation across Interface in Glass," Proceedings of Korean-American Scientists and Engineers Conference.

Number of Papers published in non peer-reviewed journals: 1.00

(c) Presentations

W. Chen, "Interactions between an Advancing Crack and an Interface Perpendicular to the Crack Path," Army Transparent Armor Materials Working Group Meeting, University of Mississippi, May 6-7, 2009.

Hwun Park, 2010, "Production and Use of Light Gas Gun in the Study
of High Velocity Impact Dynamics," The 2010 Research Symposium Series of School of Aeronautics and Astronautics, March 23, 2010, Purdue University.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):   0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

H. Park and W. Chen, "Experiments on Dynamic Crack Propagation across Interface in Glass," 2009 US-Korea Conference (UKC) on Science, Technology and Entrepreneurship in Raleigh, NC, July 16-19, 2009.

Hwun Park, 2010, "Dynamic Crack Propagation through Interface," 34th International Conference and Exposition on Advance Ceramics and Composites, January 24-29, 2010, Daytona Beach, FL.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 2

(d) Manuscripts

Hwun Park and Weinong Chen, 2011, "Dynamic Crack Propagation through a Perpendicular Interface," International Journal of Impact Engineering, submitted.

Number of Manuscripts: 1.00

Patents Submitted

Patents Awarded

Awards

W. Chen, Seed for Success Award, Purdue University, 2008, 2009, 2010
W. Chen, CT Sun Research Excellence Award, Purdue University, 2008

Graduate Students

NAME	PERCENT_SUPPORTED
Xu Nie	0.50
Hwun Park	0.25
FTE Equivalent:	**0.75**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Wayne Chen	0.08	No
FTE Equivalent:	**0.08**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Xu Nie

Total Number: 1

Names of other research staff

NAME   PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

During the funded period of the program, a gas gun has been developed and used to impact layered glass targets. Notched glass specimens having adhesive interfaces are impacted with plastic projectiles launched by the gas gun. The impact velocity is controlled such that a well-defined crack forms at the notch tip and propagates towards the interface. It is found that, an impact-induced crack arrests at an interface perpendocular to the crack path if the interface is not bonded. When the interface is bonded tightly, the crack passes through the interface in its propagation without being affected by the interface. When the bonded interface has a finite thickness, the crack slows down at the interface and then branches to many cracks that form a fan shape.

Besides the crack experiments, the effects of surface quality on bending strength of glass are also investigated. The tensile surfaces of four-point bending and ring-on-ring bending specimens are prepared to a variety of surface finish. The specimens are then subjected to bending loads at various loading rates. It is found that higher loading rates lead to higher bending strengths. More remarkably, when the tensile surface is chamically etched, the bending strength is five times higher than the samples with polished surfaces and an order of magnitude stronger than the samples with rough surfaces.

Technology Transfer

US Army Research Office
Dr. Ralph Anthenien
P.O. Box 12211
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Period of Performance: 01 October 2008 through 30 September 2010

Final Report

Effects of Surface Treatment and Interfacial Strength on the Damage Propagation in Layered Transparent Armor under Impact

Submitted by:
Weinong Wayne Chen, Principal Investigator
Professor of Aeronautics, Astronautics, and Materials Engineering
765-494-1788 ph • 765-494-0307 fax • wchen@purdue.edu

Purdue University
School of Aeronautics and Astronautics
School of Materials Engineering
College of Engineering
3323 Neil Armstrong Hall of Engineering
701 West Stadium Avenue
West Lafayette, Indiana 47907-2045

20 March 2011

Executive Summary

Effects of Surface Treatment and Interfacial Strength on the Damage Propagation in Layered Transparent Armor under Impact

PI: Weinong Wayne Chen, Purdue University

The goal of this research program was to develop a fundamental understanding of the damage propagation through layered transparent armors under impact loading conditions. This goal was to be achieved the controlled impact experiments on layered glass structures with varied surface quality and interfacial bonding strength, which would allow the examination of dynamic damage propagation or arrest in the structures. Due to the limited amount of funding received, we were able to develop the experimental techniques proposed for the impact experiments and conducted dynamic impact experiments on layered glass specimens under a limited set of conditions. Based on the experimental results, one journal article has been accepted for publication. In addition, we collaborated with researchers at Pacific Northwest National Laboratory (PNNL) and Southwest Research Institute (SwRI), who were separately funded, to develop analytical and numerical models for the dynamic damage in glass under impact. The results of the collaborations have led to three journal papers.

On the focus of dynamic damage propagation in a layered structure, we investigated the dynamic crack propagation across an interface is investigated to understand the interaction between a propagating crack and an interface in glass under impact loading. Notched glass specimens having adhesive interfaces were impacted with plastic projectiles on the notches. Cracks developed from the notch tips and propagate into the interfaces perpendicularly. The patterns of crack propagations across the interfaces depended on the interface types. The crack stopped at the interface without adhesive. The crack passed across the interface with a very thin layer of adhesive. The crack branched into many cracks after it passed across the interface with an adhesive layer of finite thickness.

For the collaborations with PNNL and SwRI, we conducted ring-on-ring bending experiments over wide ranges of loading rates and surface conditions to provide experimental insights for analytical and numerical modeling for glass.

This report summarizes the technical achievements realized during the performance period of this research program. All the results have been transferred to TARDEC (Dr. Doug Templeton), PNNL (Dr. Xin Sun), and SwRI (Mr. Tim Holmquist), assisting the analysis of impact response of structures that are of interest to US Army.

1   Table of Contents

2   Introduction

When a layered transparent armor is impacted by a projectile or fragment, the brittle material directly ahead of the projectile will be damaged extensively due to intensive shock loading. In a layered structure, the brittle armor materials are laminated together with thin ductile layers in between. Due to the existence of the ductile layers, the propagation pattern and speed of the damage propagation in the brittle material is altered. Since the eventual failure of the transparent armor is directly related to the propagation of damage through the target, it is critically important to understand the dynamic damaging process. Quantitative descriptions of the dynamic damaging process are currently not available. In this section, we briefly review the background, the knowledge available in the literature and the need for innovative exploration for damage propagation in glass.

2.1   Background

2.1.1 Layered Structures for Impact Resistance

Some transparent materials, such as aluminum oxynitride (AlON), glass, sapphire and spinel are hard and brittle. Some others, such as Plexiglas, polycarbonate, and polyurethane, are soft and ductile. If the materials are in the form of thin sheets, upon ballistic impact, the hard/brittle materials will shatter whereas the soft/ductile will be punched through. If the sheets are sufficiently thick, either type of the materials can stop penetration by an incoming threat. However, for future applications of transparent armors in land and air platforms, weight is a critical parameter that must be minimized (Patel and Gilde, 2002). With the weight restriction, materials must be used wisely in an armor system to utilize the specific strength of each material to full extent. Since four decades ago, it has been known that adding a ceramic plate on top of a metal plate can significantly enhance the ballistic protection over the monolithic metal armor (Mascianica, 1964; Wilkins et al., 1967-1971, Gooch, 2006). Upon impact, the hard ceramic plate surrounding the impact area may be fractured, pulverized, and ejected depending

Fig. 1: Damages in transparent armors from ballistic impacts: single hit (top) and multiple hits (bottom).

on different impact conditions. However, the dynamic failure processes of the brittle layer effectively extend the time of impact loading and spread the impact load over a larger area on the backing structures. Both the loading time extension and the impact area increase reduce the
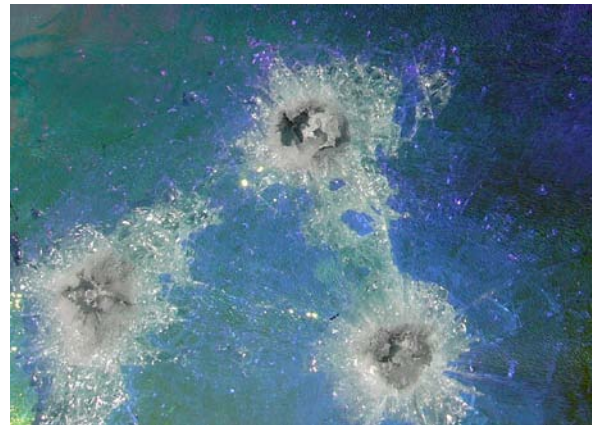
stress on the backing structures, thus enhancing the possibilities of defeating the threats. The fracture and pulverization of the ceramic material are also effective ways to dissipate part of the kinetic energy (KE) brought by the projectile. Further, the flow motion of the hard ceramic fragments around the projectile erodes the tip or even the entire length of the projectile, which further dissipates energy and spreads the impact area. This layered armor concept has been used in many vehicle and personnel armor designs. Figure 1 shows two pictures of glass windows laminated with glass sheets with thin layers of polyurethane in between. A polycarbonate backing plate is attached to the back side to stop spall debris. The picture on top is the damaged window by a single bullet impact. The lower picture shows the damage status of multiple hits. The fact that the window did not shatter completely after first hit and was still capable of bearing subsequent hits clearly shows the effects of laminated structures in impact resistance. McCauley et al. (2005) used high-speed images taken from the side view of a layered glass structure to show that the layers did not alter the impact-induced stress wave propagation significantly. However the damage in the glass was developed extensively in the first layer before propagating into the second layer. It was found that even ductile

Fig. 2: A layered polycarbonate window that defeated three shots from small arms.

sheets benefit from laminating to improve the impact resistance. Figure 2 shows the picture of a laminated polycarbonate window that stopped three shots from small arms. From the top edge of the window, the lamination structure is clearly seen. One of the defeated projectiles is displayed on top of the edge. The observation shows that adding interfaces in ductile laminates also changes the impact resistance.

2.1.2 State-of-the-Art of Layered Glass Structures

While advantages of laminated structures in penetration resistance have been recognized and utilized in many armor applications, the fundamental and quantitative understanding of lamination has not been completely developed yet. Most of the previous research efforts have been focused on the elastic or acoustic wave propagations through layered media (e.g., Sun et al., 1968; Ben-Amoz, 1975; Cetin, 1994; Nayfeh, 1995; Tadi, 2004). As the amplitudes of stress waves increase, materials in the layers start to fail. Cone crack propagation in the brittle phase of a layered structure was studied by Han (2000). At even higher loading levels, Zhuang et al.,
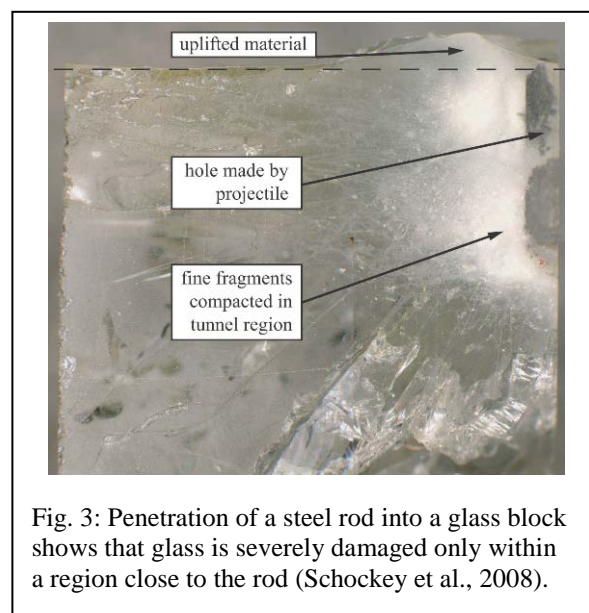

Fig. 3: Penetration of a steel rod into a glass block shows that glass is severely damaged only within a region close to the rod (Schockey et al., 2008).

(2003) investigated the shock wave propagation through periodically layered composites under uniaxial strain conditions. Due to the existence of the layers, the amplitude of the propagating stress was found to decay exponentially (Barker et al., 1974). Lamination also causes resonance in the layers (Lundergan and Drumheller, 1971; Oved et al., 1978).

Although stress wave propagations in layered media have been extensively investigated, the loading conditions for those studies are typically quite different from those encountered in penetration events. Under projectile impact loading, the load intensity varies significantly in the target, with the most severe conditions just ahead of the projectile. The materials that are severely loaded will be extensively damaged and displaced, leaving the necessary cavity opening to accommodate the advancing projectile. The materials that are away from the projectile may remain intact. Figure 3 shows an image of a glass target section after a steel projectile entered a glass target. The experiment was performed at SRI (Schockey et al., 2008). The arrested projectile is positioned vertically on the right side of the image (only half of the target is shown due to its symmetry). The heavily damaged glass becomes bright while intact portion is still transparent. The image in Fig. 3 shows that the heavily damaged zone in the glass is only a few projectile diameters around the projectile. When the target is laminated, instead of bulk, glass, the damage in the glass material in the target is much more widely spread, as shown by the experiments performed at IAT (Bless and Chen, 2008).
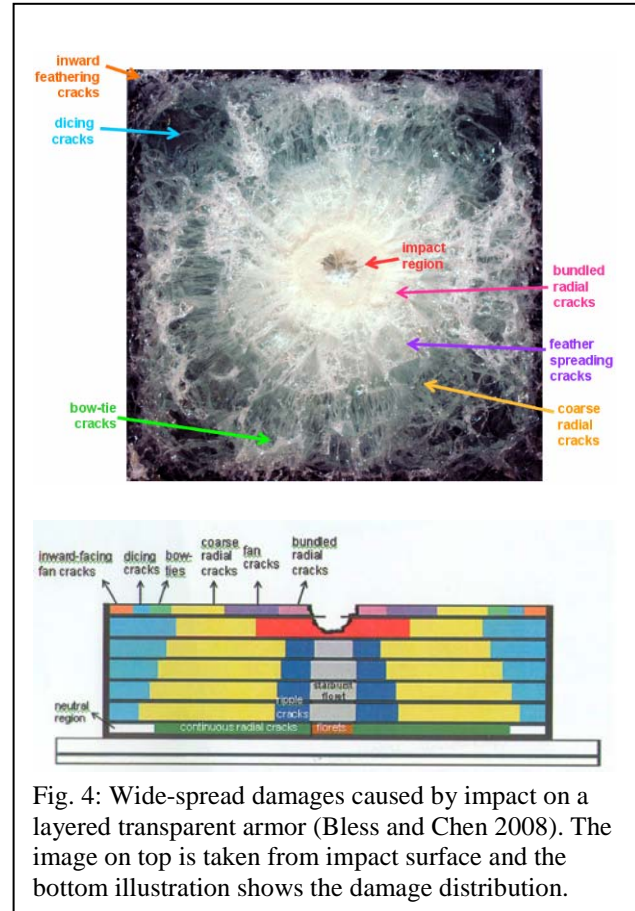

Fig. 4: Wide-spread damages caused by impact on a layered transparent armor (Bless and Chen 2008). The image on top is taken from impact surface and the bottom illustration shows the damage distribution.

From the analysis of this very recent experimental evidence, we *hypothesize* that the critical physics in the penetration of a brittle or layered target is the damage propagation. It is the motion of the damaged material ahead of the projectile that allows the projectile to move forward. If the damage zone is localized, such as those encountered in the glass-block target (Shockey et al., 2008), the material within the zone is extensively damaged and can be moved around the projectile relatively easily. This leads to deeper penetration. In the case of the layered glass target (Bless and Chen, 2008), the damage in the target is much more wide-spread, which dissipates more energy from the projectile, leading to less penetration and thus a more effective armor. It is therefore critical to understand the effects of layered structure on the formation and propagation of damage. It is also of significant interest to identify important parameters, such as surface quality of each layer and the interface strength between layers. However, damage formation, damage propagation, and damaged material motion in a layered target have not been well understood. Most of the research in this area is in armor industry with attempts to optimize the use of layer thickness and hardness (ArmorChallenge 2007) through trial-and-error.

2.1.3 Experience of the Purdue Team on Glass Characterization

Our research group has extensive experience characterizing the dynamic response and failure behavior of glass materials for transparent armors. We describe two recent projects here. The first one examines variation in dynamic compressive strength of a borosilicate glass as a function of the shear component in the stress state. The other is the effects of surface quality on the dynamic tensile strength of the same borosilicate glass.

Most mechanical experiments subject the specimens to well-defined stress states, such as uniaxial stress or uniaxial strain. Due to the complicated stress states the glass target experiences in an impact event, the glass response under more complex stress states is of interest. One way to quantify the stress state is to monitor the amplitude of the shear stress component. The main approach to decrease the effective shear stress in a compression experiment is to apply lateral confinement on the specimen while the specimen is axially compressed. A few experimental techniques are available to achieve this purpose. For example, Frew (2006) combined a hydrostatic compression chamber with a pulse shaped SHPB to determine the effects of strain rates on the dynamic stress-strain behavior and brittle-ductile transition on a lime stone. Lateral confinement by electro-magnetic forces

Fig. 5: Strength of a borosilicate soda-lime glass decreases with increasing shear stress in the sample stress state.

(Chen, 1999) and by mechanical collars (Chen and Ravichandran, 1996; Dannemann et al., 2006) is other available methods. The increase in the normalized shear is less common but is also an important stress state that needs to be explored. We (Nie et al., 2007) used an inclined specimen in a pulse shaped SHPB to explore the dynamic fracture initiation and development during compression/shear loading on a borosilicate glass specimen, as shown in Fig. 5.

The glass specimens were 9 mm by 9 mm in cross section and 12.5 mm in length. For the experiment presented in Fig. 5, the specimen axis was tilted 7° from the compressive loading axis. The dynamic compressive loading from the SHPB had a linear ramp shape, which deformed the brittle specimen at a nearly constant average strain rate under a dynamically equilibrated stress state. The compressive strength corresponding to the damage initiation as a function of shear stress is shown in the lower figure which illus tracts the trend that the dynamic compressive strength of the borosilicate glass decreases with increasing shear stress. Thus, the compressive failure strength of the borosilicate glass is sensitive to the imposed shear component.

When the applied stress is tension, we examined the dynamic tensile strength of the borosilicate glass using a four-point bending configuration. To examine the surface-quality and loading-
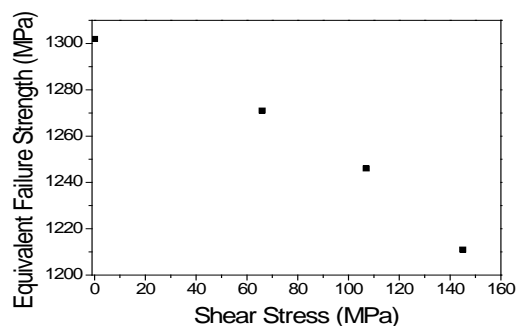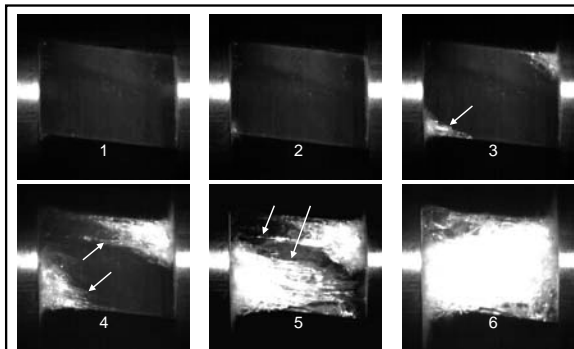
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rate effects, we prepared the tensile surface of the bending specimen with grinding of different sand papers and chemical etching, and load the sample at four different loading rates. The top two images in Fig. 6 are high-speed images of the four-point bending specimens at the instant of failure under stress-wave loading. Due to the transparent nature of the glass specimen, the tensile surface of the four-point bending specimen (mounted vertically) can be see as a thin vertical line in the middle of the top left image. This tensile surface was prepared by sand-paper grinding. At this moment of failure, a short line is seen that is perpendicular to the tensile surface and located on the upper quartile along the tensile surface. This short line is the image of a single crack that breaks the specimen into two pieces under dynamic bending loading. The failure tensile stress is around 140 MPa. When the tensile surface is treated with chemical (5% HF acid) etching, even though the surface roughness measurements are comparable to those from sand-paper grinding, the tensile failure strength is an order of magnitude higher. The failure mode is no longer dominated by a single crack. Rather, many cracks propagate simultaneously, leading to an explosion-like failure at the peak load (top right image in Fig. 6). The graph in the lower part of Fig. 6 summarizes the effects of

Fig. 6: Dynamic tensile strength of a borosilicate soda-lime glass increases by an order of magnitude with surface treatment.

loading rates and surface treatment. Both surface treatment and loading rate significantly affect the tensile strength of the Borosilicate glass.
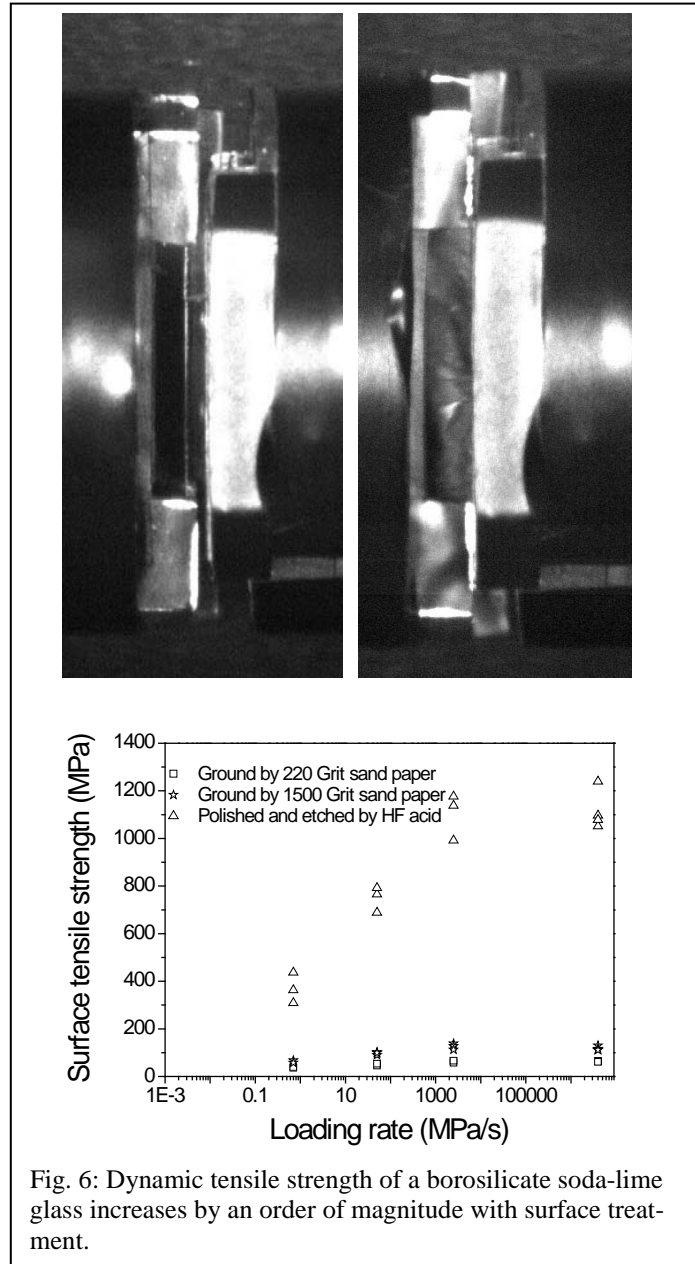
2.1.4 Numerical Predictions in Impact Damage Propagation

More quantitative efforts have been invested recently to predict the impact damage initiation and propagation in layered glass structures. For example, Sun et al. (2008) numerically simulated the case of a projectile impact into a layered soda lime glass target. The target composition is similar to that ballistically tested by Bless and Chen (2008). The numerical simulation allowed more details on the damage initiation and propagation to be revealed during the penetration process. Figure 7 shows the target cross-section at one instant during penetration. The intact

glass is shown in gray color. The damaged glass is shown in red. It is clear that the damage initiation in the layered far ahead of the projectile. By the time the projectile arrives, the damaged zone has already spread sideways, The is quite different from the more localized damage zone in the experiments performed by Shockey et al. (2008) on a single glass block without layers (Fig. 3). Sun et al. (2008) also pointed out that the depth predicted by using a one-parameter materials model was very close to that predicted using more elaborated models. However, the damage zone predictions from one model to another were rather different. This fact indicates that more systematic experimental data are needed to establish more reliable material models for brittle materials under impact loading conditions.
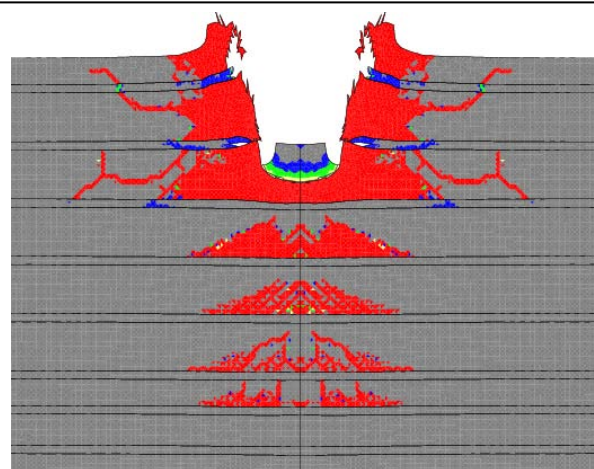

Fig. 7: Numerical simulation of a layered glass structure by Sun et al. (2008) shows the predicted propagation of impact damage.

2.3   Need for Dynamic Property and Damage Characterization

Although glass has been widely used as transparent armor materials due to its cost effectiveness, the understanding of the impact response of glass is still very limited. Predictive capabilities have not been developed with high confidence for design applications. As pointed out earlier, systematic experimental research is still in need to reveal the physical nature of the glass deformation and failure under impact and to provide reliable data input for realistic numerical simulations of the impact response of glass structures. In this report, we summarize progresses in two major aspects: (1) the interaction of a dynamic crack with an interface perpendicular to it in a glass target; and (2) equi-biaxial strength of a borosilicate glass over wide ranges of loading rates and surface quality conditions.

3   Technical Approach

We present the background and experimental design for each of the two aspects investigated in this research program. The first is to extend one of the equi-biaxial bending techniques (ring-on-ring) into dynamic loading rates such that the bending strength of a glass specimen can be determined as a function of loading rates with the edge effects. The surface conditions on the glass specimen are systematically controlled such that the more intrinsic glass tensile strength can be explored. The second is to develop a new experimental method to study the interaction between in impact-induced dynamic crack and a perpendicular interface in the glass target. The isolation of a single crack provides a platform for more quantitative observation on the behavior of the moving crack.

3.1 Dynamic Bending Strength of Glass

3.1.1 Dynamic Ring-on-Ring Experimental Setup

In a previous study (Nie et al., 2009), uniaxial four-point bending tests were carried out on the same material with an in-house made loading fixture in the testing section of a Kolsky bar. It was found that at a certain stress level, the fracture origins universally shifted from central surface to the edge, presumably due to the competing failure mechanisms between surface flaws and edge flaws. However, with the interference of edge failure, the flexural strength measured in those tests are considered to be lower than the intrinsic surface tensile strength due to the fact that the stress on the edge is concentrated and does not reflect the global tensile stress on the surface. Therefore, a new flexural testing technique without the influence of edge flaws is desirable for the characterization of dynamic flexural strength of borosilicate glass when surface-located flaws are strength-limiting. In this study, an equibiaxial ring-on-ring testing fixture was developed and introduced to a modified Kolsky bar. A pair of concentric steel rings was attached to concentric aluminum substrates on the Kolsky bar so that the system alignment is secured. The rings were hardened to HRC 60 and then polished to ensure smooth contact with glass samples. The diameters of those concentric rings are 12.5 mm and 25 mm, respectively, with a ring tip radius of 2.5mm. The incident and transmission bars of the Kolsky bar setup are made of 6061-T6 aluminum alloy with a common diameter of 31.75 mm. An image of this testing configuration is shown in Fig. 8. In addition to the ring fixture, a pair of universal joints which are of the same diameter of the bars was also placed between the gage section and the transmission bar. Universal joints were adopted in Kolsky bar system to eliminate possible misalignment in the gage section (Chen and Song, 2011). This modification is very important in brittle material testing because these materials are susceptible to failure initiation from concentrated stresses. If the stress distribution in the specimen is nonuniform, premature failure may occur even when the global stress level is still low. The joints used in this research are composed of a convex plane and a concave plane which are of equal curvature and facing each other. During specimen-installation, this pair of surfaces is the last to engage, eliminating misalignment and ensuring an even contact between the loading rings and the specimen surface.
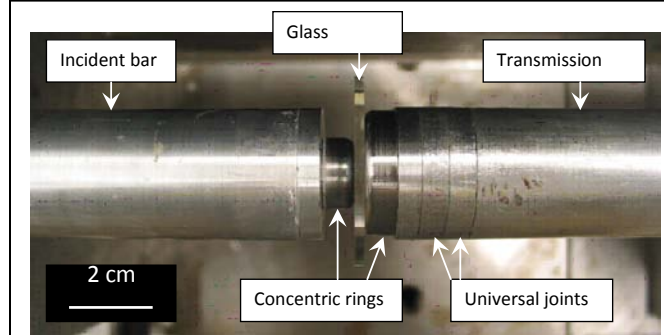

Fig. 8: An image of dynamic ring-on-ring experimental setup.

To eliminate the inertia effects on the test section, an annealed copper disk pulse shaper of 1-mm thick and 3.3 mm in diameter was used to generate the desired incident ramp pulse at a resultant specimen loading rate of approximately 5×10^6 MPa/s, while not exciting any resonance mode in the test section of the loading/supporting rings and the disk specimens. The pulse shaper also controls the profile of the incident pulse such that the specimen is under dynamic force equilibrium, enabling the use of quasi-static data reduction schemes.

3.1.2 Specimen Preparation

The borosilicate glass used in this research is provided by U. S. Army Research Laboratory, Aberdeen Proving Ground, MD, in the form of 3.3-mm thick flat plates. The material composition and specifications can be found in a previous paper studying the shear-stress effects on the compressive strength of the same glass [2]. These glass plates were machined to disks of 2 mm in thickness and 45 mm in diameter, with the top and bottom surfaces being mechanically polished to 40/20 scratch/dig and the overall surface roughness to be less than 20 angstroms. In order to reduce the possibility of edge failures, the circumferences of the disks were fire polished to eliminate sharp surface cracks induced by grinding. The as-polished samples were then divided into 3 groups. The first group stayed at the original as-received state and was tested without further surface modifications. The second group of samples was ground by 180-grit sandpapers to intentionally introduce surface flaws. The last group was etched by 5 w.t.% of HF acid aqueous solution for 15 minutes. This specific modification is performed to either completely remove or significantly blunt the pre-existed surface flaws by stripping off the glass surface layer by layer during etching. The etching process results in a 20-μm reduction in thickness at each surface of the samples. To avoid the possible moisture interaction with etched glass so as to inhibit the formation of new surface cracks, the etched specimens were subjected to mechanical loading within several minutes after etching.

3.1.3 Testing Conditions

Quasi-static experiments were carried out on a servohydraulic testing machine with the same loading configuration as implemented on Kolsky-bar setup. In both dynamic and quasi-static experiments, cellophane tape was applied to the compressive surface of the bending specimen to retain fracture fragments. The ring-specimen contact surfaces were lubricated by vacuum grease to minimize friction effects. The temperature of the testing environment was 26°C, with a relative humidity of 34%. Dynamic experiments on the Kolsky bar were conducted at a loading rate of approximately 5×10^6 MPa/s.

Fractography was conducted on fracture surfaces to study the failure origins and types of surface flaws that initiated the fracture. Only the experiments where specimens failed within loading ring area were considered to be valid tests. Radial fracture pattern of the fractured samples point to the location of failure initiation. The glass pieces were taken apart from the tape with extraordinary care to preserve the fracture surface. Optical microscope was used to identify the exact failure origin on the fragments where fracture was initiated. Selected fracture origins were further investigated by scanning electron microscopy (SEM) to define the types of flaws.

3.2 Impact-induced Crack through a Controlled Interface

3.2.1 Impact Experimental Setup

In this study, we attempt to investigate the interaction of a dynamic crack in glass with a perpendicular interface. The crack is initiated by projectile impact. The behavior of the crack propaga-

tion and its interaction with the interface is recorded by an optical high-speed camera. In many studies, the impacts to initiate the crack were at relatively low speeds (as low as 10 m/s) (Theocaris and Milios, 1981; Xu and Rosakis, 2003; Ravi-Chandar, 2004). However, the failure waves in glass are typically initiated by much higher impact speeds (Brar, et al., 1991; Kanel et al., 2004; Willmot and Radford, 2005). In this study, to observe crack behavior in glass, which is initiated by impact conditions more consistent to failure waves, we aim at impact velocities beyond one tenth of the crack speed. To produce such high-speed and consistent impacts, a light gas gun was employed. The arrangement of the gun, a specimen and a high speed camera in the experiments is schematically presented in Fig. 9. The gas gun propels a projectile onto the notched edge of the glass specimen. When the projectile passes through two pairs of lasers and sensors,
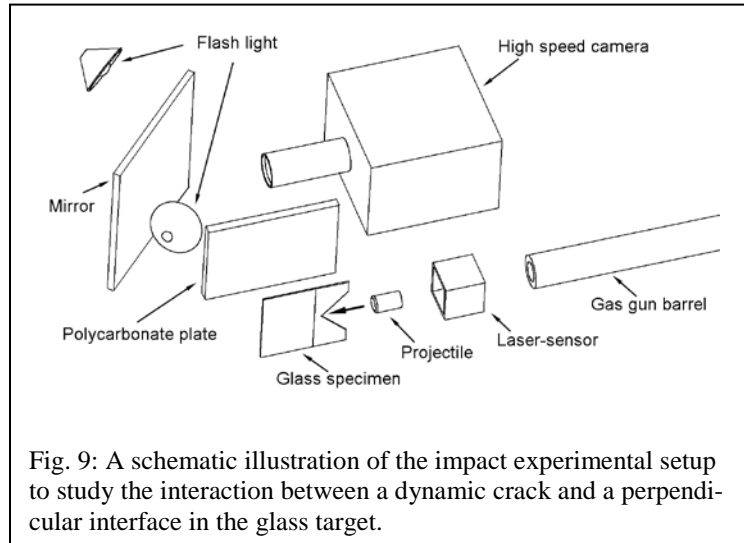

Fig. 9: A schematic illustration of the impact experimental setup to study the interaction between a dynamic crack and a perpendicular interface in the glass target.

the interrupting sequence of the lasers and the time in between determine the speed of the projectile. The high speed camera is triggered by the signal of laser interruption. After a pre-calibrated delay time, the camera starts to record the images of dynamic cracking at the moment when the projectile impacts the specimen. The camera records 32 images from each impact event at an adjustable inter-frame interval of as low as 5 μs. Strong flash lights are used to illuminate the specimen for the high-speed camera to capture the fracture events. After the impact, the debris of the glass specimen is carefully collected to study the fracture surfaces left on the glass specimen by the dynamic fracture events. These impact experiments can produce significant blasts and debris that might damage the recording equipments. To avoid such damage, all impacts are contained in an enclosed steel chamber that has thick polycarbonate windows for optical observations. Furthermore, the high-speed camera is positioned away from the specimen chamber. A mirror is used to reflect the fracture event into the camera's aperture (Fig. 9).

3.2.2 Specimen Design

Figure 10 illustrates the dimensions of a projectile and a specimen that are used in the impact experiments. Specimens were fabricated from 6.4-mm thick commercial soda-lime glass plates. As shown in Fig. 10, two glass plates were bonded with an epoxy adhesive (Loctite E-30CL) along their contacting edges. When the projectile impacts the notched edges of the specimen, compressive waves are generates and propagate radially from the impact points. When the compressive waves reach the free edges of the specimen, tensile waves are reflected back towards the crack. The interaction of the tensile waves with the propagating crack will complicate the loading conditions at the crack tip. The specimen is designed to be large enough to avoid the interaction between the tensile waves and the crack during the window of observation. The wave speed c in the glass is estimated to be 5430 m/s (Willmot and Radford, 2005). As it will be shown later,

the observation time window Δt in the experiments for the crack to interact with the interface is about 60 μs. Therefore, the minimum width d of the specimen should be approximately

$$d = c\Delta t = 0.326 \quad (m) \tag{1}$$

The actual specimen width is 305 mm, which is sufficient to provide the minimum time window. Similarly, the length of the second (un-notched) piece of glass plate must prevent the tensile wave reflected from the far edge of the sample to reach the interface before the crack under investigation has passed through. This criterion determines that the minimum length of the second glass plate to be 163 mm. The actual dimension used is 203 mm (Fig. 10). The angle of notch is 90°. A notch angle of either larger or smaller does not produce the desired single-crack initiation from the notch tip. After trial experiments, the angle of 90° was selected. To ensure constant dimensions and straight interfaces, the as-received glass plates were trimmed by a water-jet.

Fig. 10: Specimen design in the impact experiments.
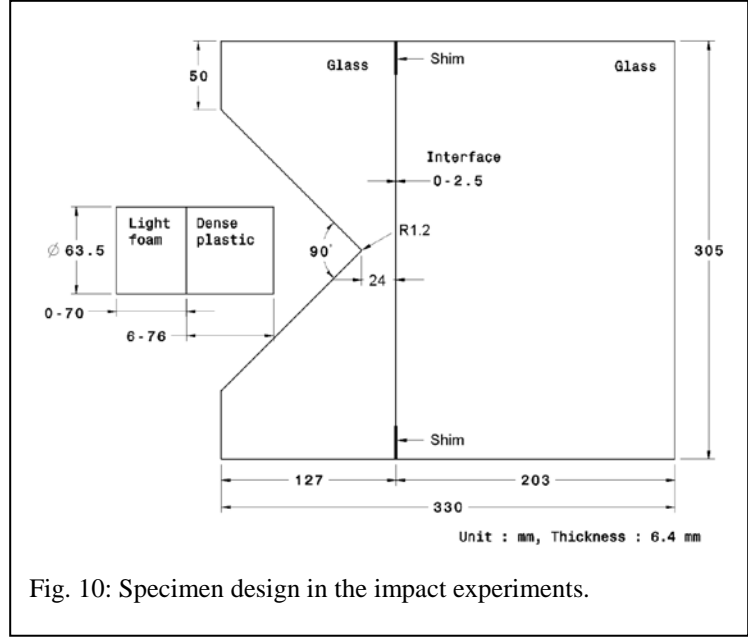
To study the effects of interface, the interface thickness was varied by inserting shims of standard thickness between the two glass plates near the side boundaries of the specimen (Fig. 10). Epoxy was applied on the contacting edges of the plates. The two glass plates were then pressed against each other (separated by the shims if a given width was desired) while the epoxy cured. The specimen where the interface was bonded without any shim was called a specimen with a near-zero-thickness interface even though an average thickness of the adhesive layer was measured around 0.05 mm. This small thickness came mainly from the roughness of surface resulted from water-jet trimming.

In the experiments, the thickness of the adhesive layer was a parameter that was varied. Two adhesive strengths were used: unbounded or bonded. The adhesive was selected that the adhesion was sufficiently strong such that the specimens would not have any cohesive and interfacial failure. Post-mortem inspection on recovered specimen pieces validated that all failures around the interface occurred in the glass plates but not inside the adhesive layer. Among the bonded specimens, four thicknesses were used: near-zero, 0.13, 1.3, and 2.5 mm. It was expected that the thickness was an important factor that would influence the wave interactions between two glass plates and the interaction between the propagating crack and the interface.

3.2.3 Projectile Design

Due to the brittleness of the glass plates, the materials to make the projectile are required to have low hardness and low strength to prevent significant damage on the glass edges where the projectiles initially contact. Trial experiments were conducted to selected projectile materials that would not cause fragmentation on the contact points of the glass specimen, but would effectively initiate a single crack from the notch tip in the glass plate. A casting polyurethane with the trade name of "Smooth-On Featherlite" was selected as the projectile material for its low hardness and light weight. High speed images and post-mortem observations verified that the cracks were generated at the notch first, but not at the contact edges between the projectile and the specimen.

The length of projectile controls the duration of impulses generated from the impact. Sometimes, the length can be very short to create short-duration pulses. However, when the projectile is very short, it is difficult to maintain the projectile motion stable when traveling in the gun barrel. To give the projectile sufficient effective length to travel stably in the gun barrel, a light rigid casting foam with the trade name "Smooth-On FOAM iT 5!" is attached to the back end of the projectile. This weaker foam is crushable with low impacts and has a lower density. This extended section of the projectile assembly gives little impulse on the glass specimen.

3.2.4 Impact Conditions

To focus on the behavior of the propagation of a single crack, it is required that the projectile impact initiates only a single crack from the notch tip in the glass specimen. To explore the impact conditions for single-crack initiation, trial impact tests were conducted on monolithic glass plates which had notches but without any interfaces. The projectile of 63.5 mm in diameter and 13 mm in length was made with the casting polyurethane. A light-foam extension was attached to the back end for stable acceleration in the gun barrel. The total weight of the projectile assembly was 55 g. When the projectile was launched at speeds slightly above one tenths of the re-
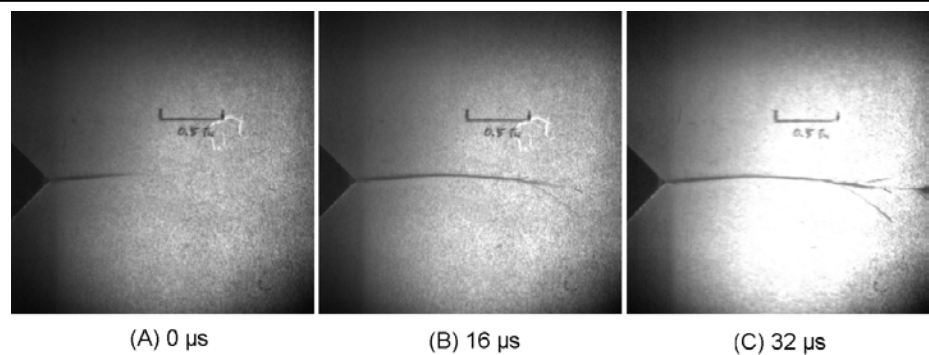

Fig. 11: Adjusting impact conditions for generating a single dynamic crack.

ported crack speed in glass, a single crack was observed to initiate from the notch tip of the specimen. The high-speed images shown in Fig. 11 were taken from a trial experiment where the impact speed was 171 m/s. Due to the low strength and low hardness of projectile, the glass specimen was not damaged in the contacted region. Instead, the foam projectile was bisected by the edges of the glass specimen. As shown in Fig. 11, only a single crack initiated at the notch and propagated through the glass specimen, although the crack branched into multiple cracks during the later stages of propagation. The sequential images at a fixed inter-frame rate provide the opportunity to measure the crack speed as it propagates through the specimen. However, in the at-

tempt to obtain the crack speed, it is very challenging to position the exact crack tip locations in the glass plate from the high-speed images because the tip is extremely sharp. Furthermore, many micro cracks may exist in front the tip. To find the exact position of a crack tip, an image of the specimen containing a crack and an image of in intact specimen were overlapped. A graphic program was then employed to identify the differences between the two images. Among 32 images recorded by the camera, the earliest image

Fig. 12: Dynamic crack speed as a function of crack length.

where a crack could be clearly identified was labeled as the first image in the series and the time stamp was marked as zero. The difference between the positions of the crack tip in two consecutive images divided by the inter-frame time interval yields the average crack speed between the two positions.

Figure 12 shows the average crack speed in both glass plates as a function of the crack-tip position through the specimen length. An inspection of Fig. 12 indicates that the observed average crack speed is around 1500 m/s which is in close agreement to the maximum crack speed reported in normal glass (Schardin, 1959). After an interface is introduced in the specimen (Fig. 10), the impact kinetic energy is increased from the case shown in Fig. 12 such that the crack has sufficient driving force to penetrate through the perpendicular interface without deceleration.
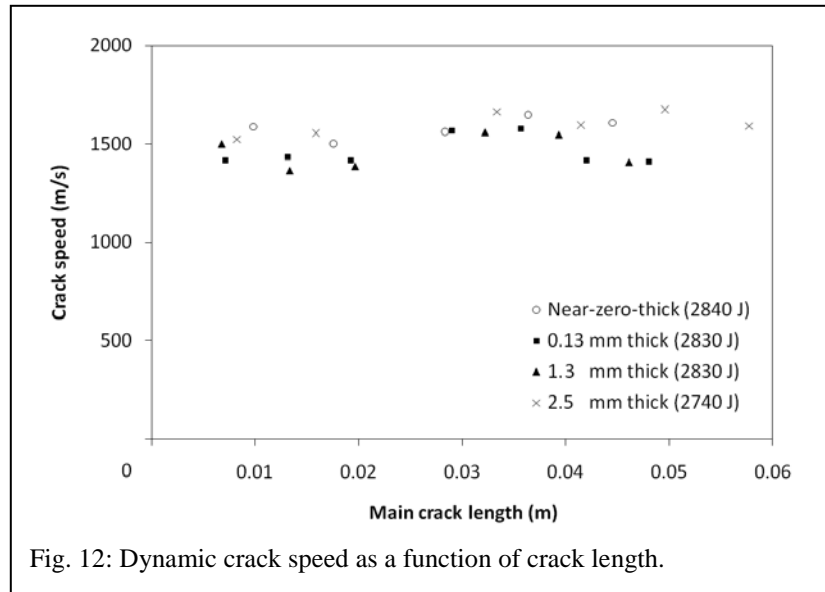
4　Experimental Results

In this section, we summarize the experimental results obtained for the two groups of dynamic experiments describe in the previous section.

4.1　Loading Rate and Surface Quality Effects on Glass Bending Strength

Equibiaxial flexural tests were conducted on all 3 groups of glass samples at 4 loading rates (0.52 MPa/s, 42 MPa/s, 3,500 MPa/s, 5×10^6 MPa/s). The three lower-rate experiments were performed on the servohydraulic machine while the high-rate experiments were conducted on the modified Kolsky-bar setup. The number of test specimens was chosen according to the specifications in ASTM C1499 such that at least 10 valid tests were secured at each loading rate and sur-

face condition. A typical oscilloscope record from a Kolsky-bar experiment on an etched glass sample is shown in Fig. 13. The incident pulse is shaped into a non-linear ramp to achieve constant deflection rate in this acid-etched specimen before sample fracture. In a dynamic equibiaxial bending test, the glass specimen is initially subjected to acceleration until the desired loading rate is achieved. Under such conditions, the loading pulse profile needs to be carefully controlled in order not to excite the resonant frequency of the testing fixture, otherwise a non-equilibrium force history will be imposed in the specimen in which the inertial force may be presented. In this

Fig. 13: Oscilloscope record of a dynamic ring-on-ring experiment.

study, the force histories on both loading-ring and supporting-ring sides were continuously monitored by the collected strain gage signals. Specifically, the force histories on the loading ring side (F_L) and the force history on the supporting ring side (F_S) are given by:
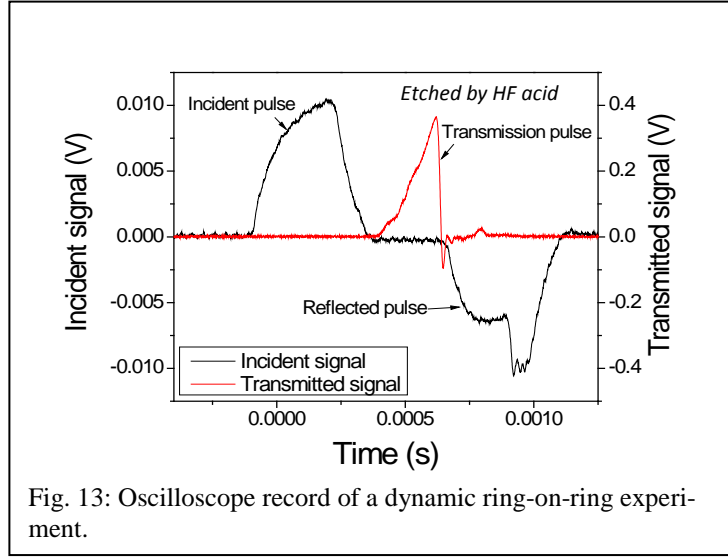
$$F_L = EA(\varepsilon_i + \varepsilon_r) \qquad (2)$$

$$F_S = EA\varepsilon_t \qquad (3)$$

where E and A are the Young's Modulus and cross-sectional area of bars, respectively; ε_t is the strain history of transmitted pulse; while ε_i and ε_r are the strain histories of incident and reflected pulses, respectively. Once dynamic force equilibrium is established, the biaxial flexural strength of the borosilicate-glass sample can be calculated by the peak load achieved in the sample in the light of circular plate theory (Timoshenko and Woinowsky-Krieger, 1959).\
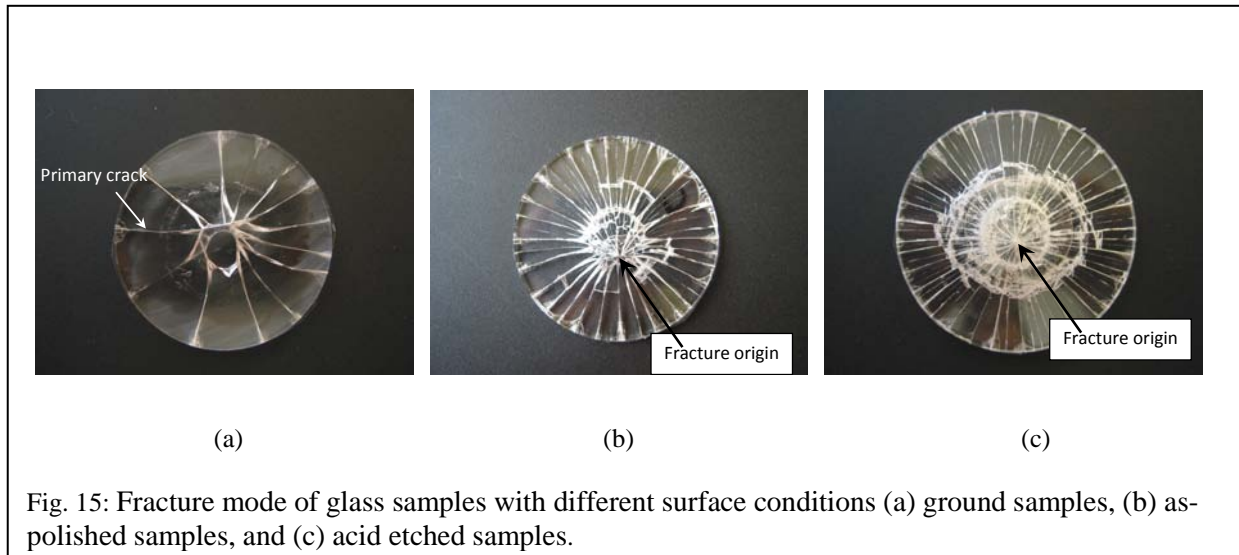
$$\sigma_f = \frac{3F}{2\pi h^2}\left[(1-v)\frac{D_S^2 - D_L^2}{2D^2} + (1+v)\ln\frac{D_S}{D_L}\right] \qquad (4)$$

where F is the peak load recorded, h is the thickness of the sample, D_S is the supporting ring diameter, D_L is the loading ring diameter, D is the diameter of the sample, and v is the Poisson's ratio of borosilicate glass.

The calculated strength values for borosilicate glass samples at different loading rates and surface conditions are summarized in Fig. 14. The scatters (error bars) in the plot represent the whole range of experimental data for each testing condition, and the symbol in between is the arithmetic average of strength. The results indicate that the surface modifications significantly affect the flexural strength of the glass material. The sandpaper grinding degrades the strength by 60-70% from the as-polished surface condition. However, HF acid etching on as-polished specimens promotes the surface tensile strength by 200-400%, depending on the applied loading rates. The experimental results also indicate that the loading rate has remarkable effects on the

Fig. 14: Loading rate and surface quality effects on the bending strength of the borosilicate glass.

flexural strength. Under all surface conditions tested, the strength universally increases with loading rates. But the rate of strength increase levels out at the loading rate of ~3,500 MPa/s.
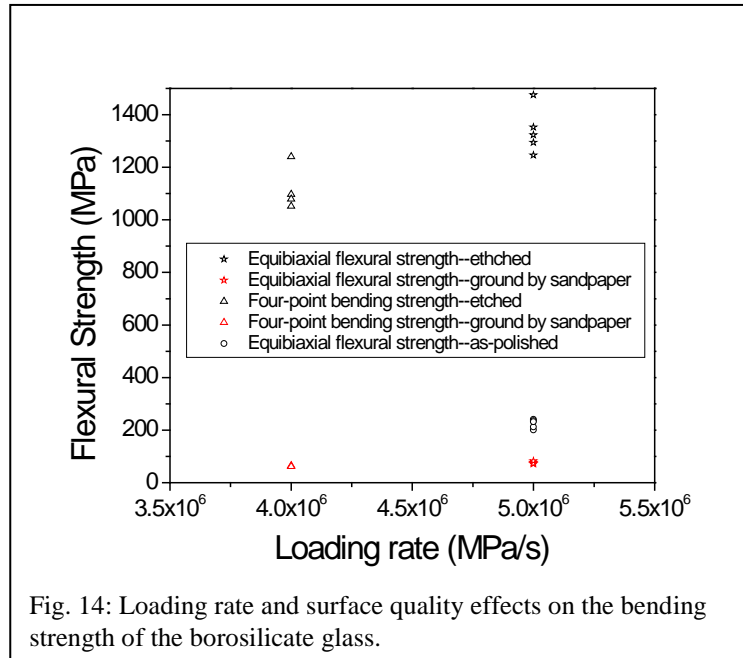
The observed strength variations under different surface conditions stimulated further fractography investigations to better understand the fracture mechanisms of borosilicate glass under equi-

(a)   (b)   (c)

Fig. 15: Fracture mode of glass samples with different surface conditions (a) ground samples, (b) as-polished samples, and (c) acid etched samples.

biaxial flexural loading conditions. A series of fractured samples from Kolsky-bar experiments are shown in Fig. 15. Since the samples were loaded by a single pulse, the fragments were well preserved after the initial fracture events. As indicated by the fracture patterns shown in the figure, the likely failure origins are all located in the central areas of specimens regardless of surface conditions. No edge failure was identified in the study reported in this paper. It is also observed that the density of cracks increases with flexural strength due to the increasing amount of elastic energy that needs to be released during fracture. As for the sandpaper-ground samples, a

primary crack (indicated by an arrow in Fig. 15 (a)) is identifiable while the other cracks were initiated at different locations along this crack. However, this primary crack becomes less distinct for the as-polished samples (Fig. 15 (b)), on which the majority of cracks were converging back to a common origin. This crack pattern finally changed into a complete radiation type for the HF acid etched samples, with essentially all cracks converged back to exactly the same failure origin (shown in Fig. 15 (c)). The transition in macroscopic cracking mode inspired further investigation on the strength-governing flaws under each surface condition. In this research, fracture surface images were taken by scanning electron microscopy (SEM) and are shown in Fig. 16. It should be pointed out that, as can be seen from Fig.15 (c), the equibiaxial bending fracture origin of HF acid etched sample is almost pulverized and thus the fracture surface around the failure-initiation flaw was heavily fragmented. For the purpose of comparison, SEM images showing the failure origins of an HF acid etched glass bar sample which was loaded in 4-point bending were therefore given in Fig. 16 (c). For the sandpaper-ground samples, sharp cracks that penetrate into the sub-surface are visible at the center of the fracture zone. These cracks are usually indications of misalignment of surface machining cracks. Further polishing on the as-ground surfaces resulted in reduction of critical crack size, and thus an increase in flexural

strength. The strength governing flaw size on HF acid etched surface is similar to that on the as-polished surface, whereas the flexural strength of the etched sample is four times higher than that of as-polished samples. It is assumed that there are sharp surface cracks existing on the machined and/or polished glass surfaces. During etching, the crack surfaces are uniformly attacked by HF acid at every point. Consequently, such a pre-crack develops into a semicircle or a semi ellipse depending on the original crack shape and etching time (over etching would more likely lead to a semi ellipse shape). Simultaneous acid attack on numerous surface cracks creates a "bumpy" surface pattern as is evident in Fig. 16 (c). According to the model, the final radii of these surface pits are determined by the depth of original flaws, so the observed variation in the pit radii may be directly related to the variation in initial crack size. The fracture surface of an etched sample reveals that failure

Fig. 16: SEM images showing the fracture origins. (a) Ground, (b) Polished, and (c) Polished and etched.

was initiated a severe surface pit. However, no sharp front of a pre-crack was identified. This indicates that the fracture of an etched specimen is originated from a blunt surface flaw, unlike
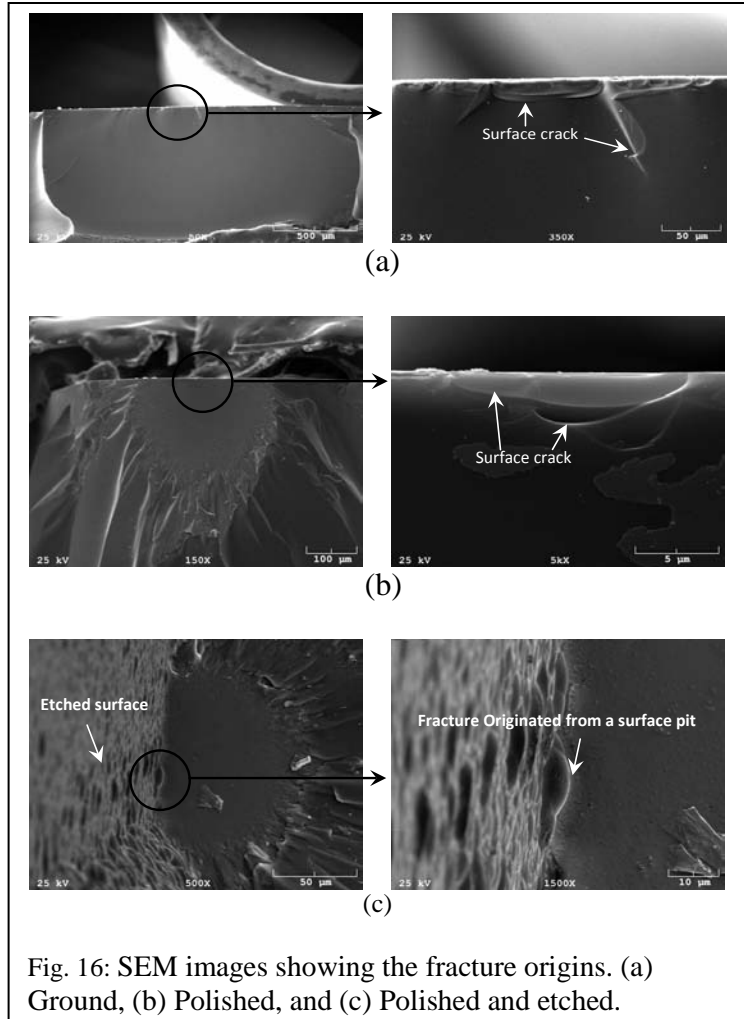
the case of as-polished specimens where a sharp surface crack is located in the failure origin. As a result, although acid etching developed similar flaw depths as is possessed by as-polished samples, the blunt nature of etching pits offers much less stress intensity compared to the sharp crack front in polished samples, and thus raises the flexural strength significantly.

4.2   Interaction of a Dynamic Crack with an Interface

After the striking velocities were explored and the high-speed camera synchronized with the projectile impact, a series of impact experiments were conducted on the specimens with perpendicular interfaces in them. The initial group of experiments covered specimen with three interface conditions: direct contact without bonding, direct bonding on the contacting edges, and bonding with a thin epoxy layer. Figure 17 shows a dynamic crack propagating in a specimen having two glass plates contacting along the interface without any adhesive layer. In the attempt to drive the crack through the contacting interface, a heavier projectile was used. The projectile had a 100-mm long front part made with the casting polyurethane and did not have any rear part made with the light foam. This projectile weighed 217 g and was also driven at a higher speed of 212 m/s. As shown in Fig. 17, a single crack was initiated at the notch and branched into two cracks, which indicated that the impact energy exceeded the level to maintain a single-crack propagation. Each branched crack propagated toward the interface, but was each stopped at the interface. Besides the initial cracks started from the notch tip, additional cracks were developed from the interface later and propagated toward the notched end (see the image (F)).
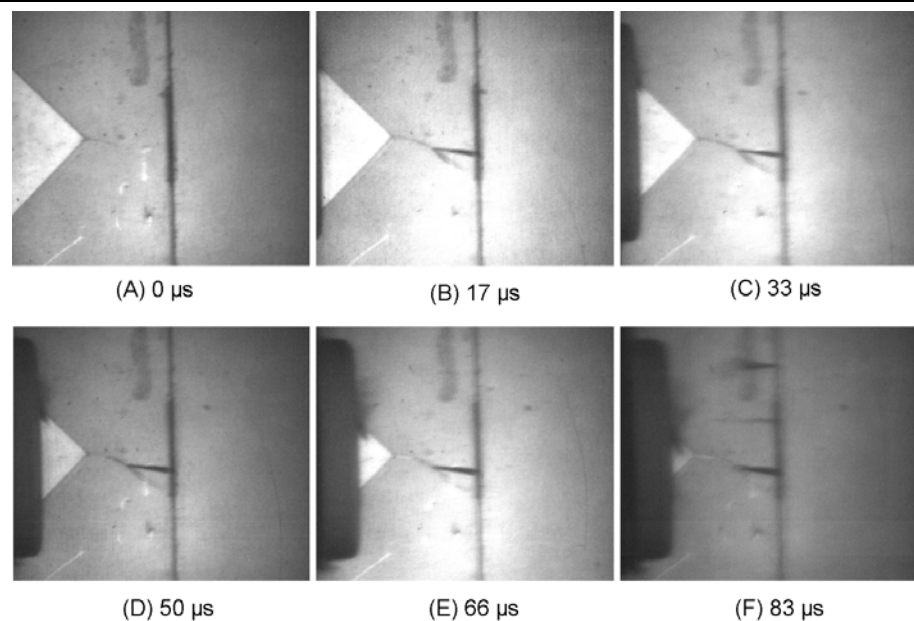

Fig. 17: Crack propagation through an interface without an adhesive layer.

These cracks were generated by the reflected tensile waves from the outer sides of the glass specimen. All the cracks were observed only in the section of the specimen between the impacted notch and the interface. The kinetic energy was 4880 J and this is much higher than any other tests in which kinetic energy is less than 3000 J. Despite the impact by a projectile with much higher kinetic energy, the interface stopped all the cracks. The second glass plate was intact. The type of crack propagation in this study was designed to be Mode I, and the projectile provided tensile loadings

in vertical direction to crack tips. These loadings cannot transfer effectively across the interface where two glass plates simply contacts without any bonding.

Figure 18 shows an experiment where a crack propagated through an interface that was directly bonded. The interface layer thickness was near zero. Trial experiments indicated that this interface made the glass behaved like a single piece. The impact conditions were adjusted
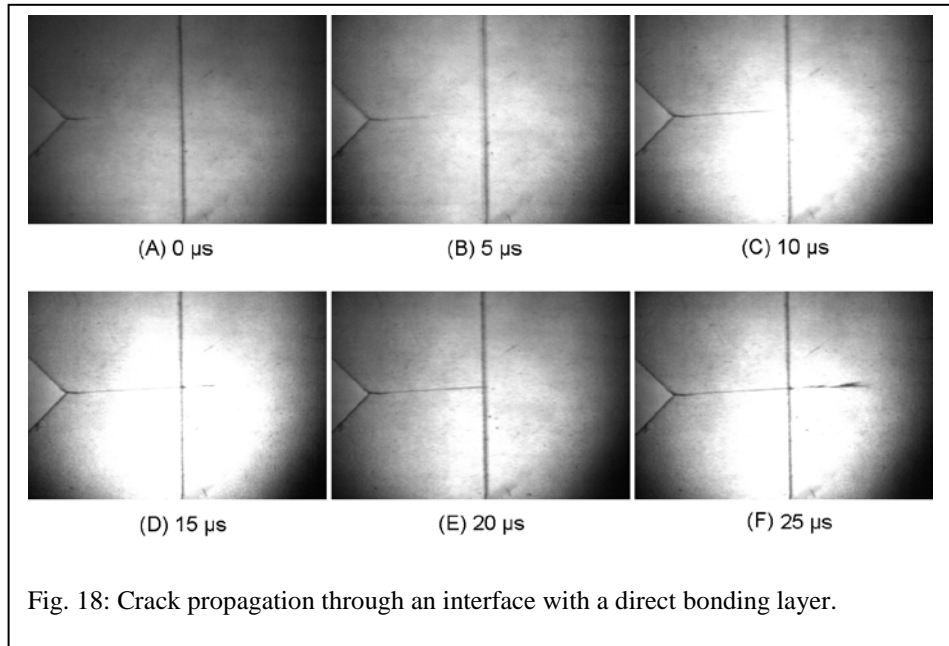

Fig. 18: Crack propagation through an interface with a direct bonding layer.

back to be closer (but still with higher kinetic energy to drive the crack to penetrate the interface) to the impact on a monolithic glass plate. The projectile had a 25-mm long front part made with casting polyurethane and 81-g total weight. It was launched at the speed of 265 m/s. Trial experiments also indicated that, if projectiles were heavier or faster than these values, the crack would branch before reaching the interface, which was to be avoided in this study.

Under impact, a single crack was initiated from notch tip of the specimen and propagated towards the interface (Fig. 18). The crack then penetrated the interface with little interference and then extended to the second glass plate. Again, the crack-
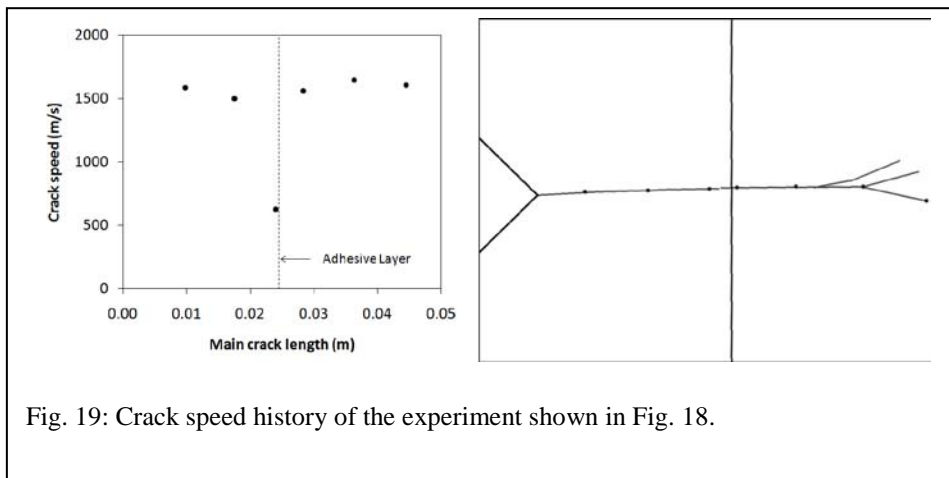

Fig. 19: Crack speed history of the experiment shown in Fig. 18.

propagation speed as a function of the tip location can be obtained from the images, as shown in Fig. 19. An inspection of the results shown in Fig. 18 and 19 indicates that the propagation of the crack had a slight delay at the interface; however, the duration of delay was so short that high speed images recorded with the frame duration of 5 μs were not sufficient to obtain the exact nature of the delay. It is evident that the adhesive layer between two glass plates transfers stress wave effectively to the second media and let crack reinitiate in the second media from the interface almost immediately. As shown in Fig. 19, the crack at the second glass plate propagated with a nearly constant speed of 1500 m/s, which was the same as the crack speed before the crack crossed the interface.

To study the effect of an interface with a thin layer of epoxy, an experiment was conducted on a specimen with an interface of a 0.13-mm thick adhesive layer. The impact conditions were nominally identical to the previous case. The projectile weighed 81 g and was accelerated to a speed of 264 m/s. Figure 20 shows that a single crack propagated from the notch into the interface. The corresponding average speed varia-

Fig. 20: Crack propagation through an interface with a thin bonding layer.

tion as a function of crack-tip positions is also plotted on Fig. 21. The results in Figs. 20 and 21 show that crack propagation was delayed for 20 µs at the interface. It is noted that the interface is thicker than near-zero-thick adhesive only by 0.13 mm. The slow crack speed in epoxy counts for the significant delay in the propagation. Also, it is evident that reinitiating crack in the second medium takes significant time because the stress intensity factor in-

Fig. 21: Crack speed history of the experiment shown in Fig. 20.

crease gradually until it reaches threshold value for crack initiation. We investigated the detail information on the crack propagation in the epoxy layer.
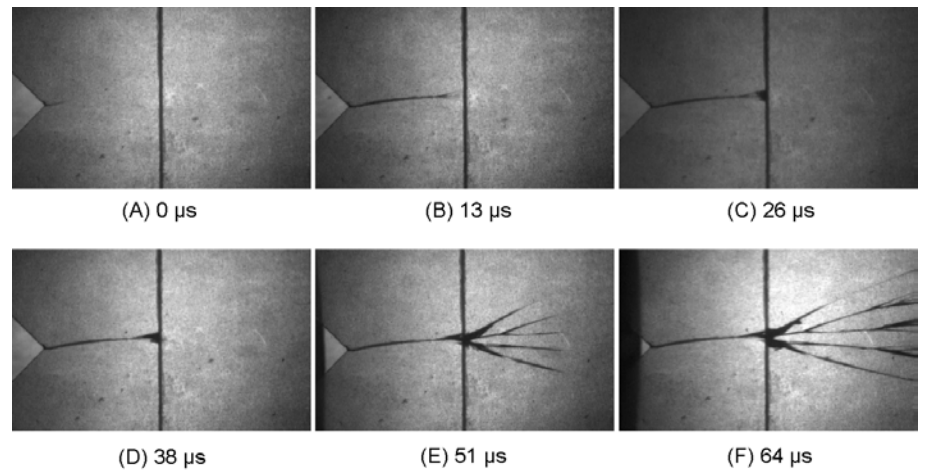
5   Summary and Recommendations

In this section, we summarize the experimental results obtained for the two groups of dynamic experiments describe in the previous section.

To study the rate and surface effects on the bending strength of a borosilicate glass, a dynamic equibiaxial ring-on-ring flexural testing technique was established on a modified Kolsky bar. The sample was subjected to a controlled loading profile such that both a constant loading rate

and dynamic force equilibrium were achieved during the entire loading period. In addition, single pulse loading technique was adopted to ensure that the glass specimen was loaded only once and therefore in the fractography point of view, the fractured samples were as pristine as they were in a quasi-static experiment. This experimental technique was then applied to investigate the effect of different surface conditions and loading rates on the equibiaxial flexural strength of a borosilicate glass. Flexural strength of 1.3 GPa at dynamic loading rates was measured on specimens where the tensile surfaces were chemically etched by HF acid. The flexural strength of the borosilicate glass increases with increasing loading rates for all the surface conditions studied. SEM images on fracture surfaces showed that the as-polished and sandpaper-ground samples failed from the sites where sharp surface machining or grinding cracks were presented. The HF acid etched samples failed, however, from blunt semi elliptical surface pits which were developed by continuous acid attack. This study shows that the weight of glass window can potentially be reduced significantly if the treated surface can be protected, such as by a sealing layer.

To study the behaviors of cracks driven by dynamic loading at interfaces, a single crack was initiated by high impact loading. The crack was found to be arrested at the interface which did not have an adhesive layer. But cracks penetrated interfaces that had adhesive layers and the penetrating behavior depended on the thickness of interfaces. With little interference, a crack crossed an interface where two glass plates touched each other along their bonding line when the thickness of adhesive layer was as thin as possible. But at the interface with an adhesive layer of finite thickness, propagation of cracks were delayed and branched into multiple cracks when they extended to the second glass plate. The delay at the interface appear to be the main reason to cause crack branching due to energy accumulation over the period of the delayed time. These experimental results were reproduced in the multiple tests where the loading conditions and the specimen configuration were almost identical. These results can serve as design guidelines for bonding layers in a multi-layer glass structure.

6   List of Publications from This Research Program

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